Fermi National Accelerator Laboratory

FERMILAB-Conf-96/391

The Fermilab Proton-Antiproton Collider Upgrades

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October 1996

Published Proceedings of the *1996 DPF/DPB Summer Study on New Directions for High Energy Physics (Snowmass '96)*, Snowmass, Colorado, June 25-July 12, 1996.

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

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ABSTRACT

The plans for increases in the Tevatron proton-antiproton collider luminosity in the near future (Run II) and the more distant future (TeV33) are described. While there are many important issues, the fundamental requirement is to produce more antiprotons and to use them more efficiently.

I. INTRODUCTION

The Tevatron antiproton collider achieved peak luminosities of 2.5×10^{31} cm^{-2}sec^{-1} in Run I, which ended in February 1996. The Main Injector and associated upgrades are expected to enable luminosities in the range of $5\text{-}8\times10^{32}$ cm^{-2}sec^{-1} in Run II, which is scheduled to begin in 1999. The Main Injector and the associated colliding beams upgrades are sometimes collectively referred to as Fermilab III. The addition of a Recycler Ring to the Main Injector project is expected to improve the antiproton utilization efficiency and increase the luminosity by a factor of 2 to 2.5.

The goal of the TeV33 project is to increase the peak luminosity to the range of 10^{33} cm^{-2}sec^{-1}. A more specific goal of obtaining 30 fb^{-1} by the year 2006 was suggested in the TeV2000 committee report [1]. The TeV33 period of collider running is also referred to as Run III. The plan for TeV33 is still being formulated, and it is too early to say specifically what goals will be reached or what the cost of the upgrades will be. However, we intend to maximize the integrated luminosity within whatever modest funding may be available.

An upgrade to a higher energy or a higher luminosity proton-proton collider is technically possible but judged to be an unrealistic competitor for the Large Hadron Collider (LHC) based on performance, cost, and schedule considerations. The plan for TeV33 is still being developed. One of the goals of the TeV33 working group is to develop new ideas and to refine existing plans. Detector upgrades are an integral part of the TeV33 plan and are being considered in conjunction with upgrades to the accelerator.

II. COLLIDER LUMINOSITY

The luminosity of the Tevatron collider may be written as

$$\mathcal{L} = \frac{3\gamma_r f_0}{\beta^*}\left(BN_{\bar{p}}\right)\left(\frac{N_p}{\varepsilon_p}\right)\frac{F\left[\dfrac{\beta^*}{\sigma_s},\dfrac{\gamma_r\sigma_s^2}{\beta^*}\left(\dfrac{\theta_x^2}{\varepsilon_x}+\dfrac{\theta_y^2}{\varepsilon_y}\right)\right]}{(1+\varepsilon_{\bar{p}}/\varepsilon_p)} \quad (1)$$

where $\gamma_r=E/mc^2$ is the relativistic energy factor, f_0 is the revolution frequency, and β^* is the beta function at $s=0$ (where it is assumed to attain a relative a minimum). The proton (antiproton) beam transverse emittance $\varepsilon_p(\varepsilon_{\bar{p}})$ is defined to be $\varepsilon = 6\pi\gamma_r\sigma^2/\beta$ for a bunch with a gaussian distribution, B is the number of bunches, N_p ($N_{\bar{p}}$) is the number of protons (antiprotons) per bunch, σ_s is the rms bunch length of either beam, θ_x and θ_y are the crossing half-angles, and $F\leq1$ is a form-factor that accounts for the depth of focus (hour glass) and crossing angle effects on the luminosity caused by non-zero bunch lengths. The bunch lengths depend on the longitudinal emittance and the rf voltage, but the luminosity depends only on the bunch length.

The formula is written in a way that emphasizes the major issues in achieving high luminosity. The first quantity in parenthesis in Eqn. 1 is the total number of antiprotons. Under current and probably future operating conditions, the most important factor contributing to the achievable luminosity is the total number of antiprotons in the ring, $BN_{\bar{p}}$. The second most important factor is the proton phase space density, N_p/ε_p, which is constrained by the need to limit the beam-beam tune shift. The formula for the linear beam-beam tune shift for collisions with no crossing angle is:

$$\Delta\nu = 6\frac{r_p}{4\pi}n_c\frac{N_p}{\varepsilon_p} = 0.0073\ (\pi\,\text{mm-mrad}/10^{10})\,n_c\frac{N_p}{\varepsilon_p} \quad (2)$$

where r_p is the classical proton radium (1.535×10^{-18} m) and n_c is the number of interaction points. Operating experience in the Tevatron suggests that the maximum tolerable beam-beam tune shift lies in the range 0.02 to 0.025. The antiproton $N_{\bar{p}}/\varepsilon_{\bar{p}}$ is also limited–although the limit on antiproton intensity imposed by production rates has traditionally been the more important limit to antiproton intensity.

While the beam-beam tune shift is interesting, the tune spread is probably of more fundamental importance. Figure 1 shows the results of a traditional calculation of tune versus amplitude (still for no crossing angle). The results are shown as a grid where the oscillation amplitude is held fixed at $0,1,\ldots5\sigma$ in one plane while it varies continuously in the other plane from 0 to 5σ. The small amplitude particles are tune shifted the most with the maximum tune shift given by Eqn. 2. The horizontal and vertical scales are normalized so that the maximum tune shift is equal to 1. The large amplitude particles are shifted the least; infinite amplitude particles have a tune shift of zero. Thus, the tune spread is nearly equal to the tune shift, and Eqn. 2 can be thought of as describing the tune spread as well as the tune shift.

In this traditional description of the beam-beam effect the second quantity in parenthesis in Eqn. 1 is not a free parameter, but is fixed by the tune shift limit. At the end of

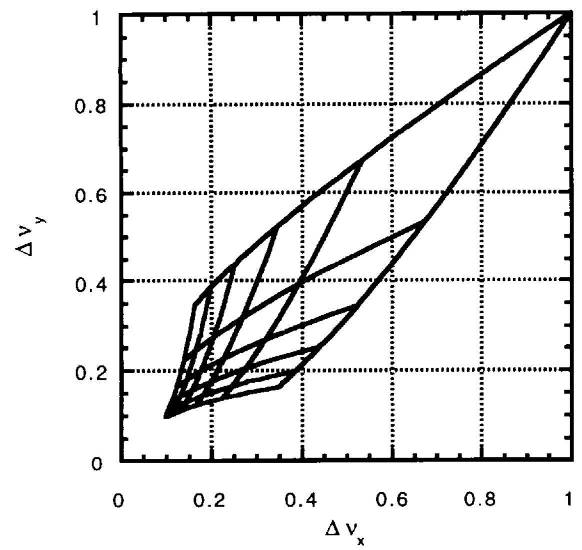

Figure 1. Beam-beam horizontal versus vertical tune. The tune is normalized to a maximum of 1 by the linear beam-beam tune shift (Eqn. 2). The tunes are shown parametrically as a grid lines of constant x or y amplitudes. Amplitudes in the range of 0 to 5σ are shown, assuming a beam with a gaussian distribution.

Run I, the Fermilab injector chain was able to equal the beam-beam tune shift limit. The Main Injector should be able to exceed this limit. However, this simple analysis needs to be refined for Run II and is, perhaps, inadequate for TeV33. In particular we need to consider:

1. The effect of the increasingly large number of long-range beam crossing points (10 in Run I, 70 in Run II, 200 for TeV33).
2. The effect of the crossing angle.
3. The effect of coupling between planes of oscillation.

One of the goals of the TeV33 working group is to achieve a better understanding of the constraints on the proton beam that are imposed by the beam-beam interaction.

Table I is the working parameter table for Run II. It illustrates the changes required to achieve the Run II luminosity goals and also the benefits of antiproton recycling. Run II requires a modest improvement in proton intensity and about 4 times more antiprotons (spread over 6 times more bunches). The antiproton stacking rate is required to increase substantially (about a factor of 3) to produce the necessary numbers of antiprotons. The Run II luminosity also benefits from the smaller (2 eV-sec) emittances expected from the Main Injector, the higher energy (1000 GeV instead of 900 GeV) Tevatron, and the higher antiproton transmission efficiency of the Main Injector.

The TeV33 parameters are, at this point, speculative. Some possible parameters are shown in Table II. The TeV33 parameter lists all have in common the need for high antiproton production rates. High antiproton intensities are needed to achieve high luminosity, but the need for high antiproton production rates is more fundamental. With efficient antiproton recycling, the most important cause for the loss of antiprotons is beam-beam collisions at the interaction point. The required antiproton production rates are computed by multiplying the loss rate from collisions at the initial store luminosity by an arbitrary factor of 2. While this number is crude–and depends on parameters like initial emittances, length of the store, and recycling efficiency–it seems clear that the antiproton stacking rate will have to be substantially increased beyond Run II levels. Another way of estimating the required antiproton intensity is to assume that the antiproton intensity will provide a luminosity increase of a factor of 5 and to scale the Run II required antiproton production rates by the same factor. This (also crude) estimate results in required antiproton production rates of about 10^{12}/hr.

Table I. Working parameter table for Run II.

Parameter	Run IB (1993-95)*	Run II (MI)	Run II (w/Recycler)	Units
Protons/bunch	23×10^{10}	27×10^{10}	27×10^{10}	
Antiprotons/bunch	5.5×10^{10}	3.0×10^{10}	7.5×10^{10}	
Req'd Pbar Production Rate	6	17	20	10^{10}/hr
Proton emittance (95%, norm)	23π	20π	20π	mm-mrad
Antiproton emittance (95%, norm)	13π	15π	15π	mm-mrad
Energy	900	1000	1000	GeV
No. of Bunches	6	36	36	
Bunch length (rms)	0.60	0.38	0.38	m
Form Factor	0.59	0.73	0.73	
Typical Luminosity	1.6×10^{31}	8.5×10^{31}	2.1×10^{32}	$cm^{-2}sec^{-1}$
Bunch Spacing	~3500	396	396	nsec
Interactions per crossing	2.7	2.3	5.8	

*Run IB column represents average of 32 stores over the period March 8-April 21, 1995.

Table II. Possible TeV33 Parameter Tables

Parameter	No Upgrades	Low Long Emittance	rf upgrade	One Experiment	Units
Protons/bunch	27×10^{10}	27×10^{10}	27×10^{10}	50×10^{10}	
Antiprotons/bunch	21×10^{10}	15×10^{10}	13×10^{10}	21×10^{10}	
Req'd Pbar Production Rate	104	108	101	51	10^{10}/hr
Proton emittance (95%, norm)	20π	20π	20π	20π	mm-mrad
Antiproton emittance (95%, norm)	20π	15π	15π	15π	mm-mrad
Beam Energy	1000	1000	1000	1000	GeV
No. of Bunches	100	100	100	100	
Longitudinal Emittance	2	0.5	2	2	eV-sec
rf Frequency	53	53	212	53	MHz
rf Voltage	1	1	8	1	MV
Bunch length (rms)	0.35	0.18	0.15	0.35	m
Crossing Half-angle	0.14	0.19	0.19	0.19	mrad
Form Factor	0.52	0.66	0.72	0.43	
Typical Luminosity	1.0×10^{33}	1.1×10^{33}	1.0×10^{33}	1.8×10^{33}	$cm^{-2}sec^{-1}$
Number of IR's	2	2	2	1	
Bunch Spacing	132	132	132	132	nsec
Interactions per crossing	9.7	10	9.5	9.6	

One of the tasks of the TeV33 working group at Snowmass is to explore these parameters is greater detail with a more realistic model.

IV. COLLIDING BEAMS ISSUES

A. Beam-Beam Interaction

The beam-beam interaction is the pre-eminent issue in the Tevatron. As the luminosity in the Tevatron rises the number of bunches is increased. The increase has been driven by the desire to keep the number of interactions per crossing low (low means about 10 for TeV33)–although ultimately one would need to increase the number of bunches to keep the antiproton $N_{\bar{p}}/\varepsilon_{\bar{p}}$ less than or equal to that of the protons. While the number of interaction regions remains at 2 (or is possibly reduced to 1), the number of beam crossing points with long-range beam-beam interactions increases with the number of bunches (it is equal to twice the number of bunches minus the number of interaction points). In Run I the antiproton bunches were subjected to 10 long range interactions on every circuit of the Tevatron. In Run II the number will increase to 70 although we have discussed running with 30×36 (antiprotons × protons) to avoid the very different tune shifts experienced by the first and last antiproton bunches.

The current plan for TeV33 is to introduce a crossing angle of about 100 μrad to minimize the effects of the parasitic crossings near the interaction region. We will try to optimize the value of the crossing angle based on the considerations mentioned below.

1. The beam-beam interaction distorts the closed orbit (up to 20 μm at low beta compared to a nominal beam size of 35 μm) and causes each bunch to have its own unique orbit.
2. The beam-beam interaction gives each bunch a unique tune: the spread in these tune shifts is about 0.01 (compared to a total tune footprint budget of 0.025). Similar results are obtained for the coupling. Chromaticities are also different for each bunch.
3. The separation at the beam crossing nearest the interaction point is determined by the crossing angle, but subsequent crossings depend also on the separator settings. The signs and strengths of the crossing angle and the separators need to be chosen to optimize the beam separation.

The results of the preliminary beam-beam calculations made to date are not sufficiently encouraging to declare success, nor are they sufficiently disturbing to terminate the plans for TeV33. The beam-beam tune shift is sensitive to many details including the size of the crossing angle and the bunch loading scheme. Much more work will be required to quantify these issues and to achieve a more attractive solution.

The crossing angle causes a reduction in the luminosity and introduces the possibility of exciting synchro-betatron resonances. These effects increase with the size of the crossing angle. The effects of the crossing angle are reduced by making the bunch length shorter. A significant Tevatron rf upgrade is the most likely candidate for reducing the bunch length. We will examine the need for an rf upgrade as a function of crossing angle.

B. Other Tevatron Issues

1. Luminosity Leveling

Luminosity leveling (reducing the peak luminosity to 5×10^{32} $cm^{-2}sec^{-1}$) is probably feasible. The penalty in integrated luminosity was estimated to be 15%. Luminosity leveling is a "detail" for the accelerator - there are many ways to level the luminosity that do not require new hardware. It might, however, be a significant consideration in detector design. We need to work out the details of possible compromises between emittance, growth rate, and initial luminosity.

It should not be supposed that luminosity leveling is trivial or even straight-forward. An enormous amount of effort is invested in minimizing beam loss by adjusting orbits, tunes, and chromaticity when the beams collide. One leading candidate to implement luminosity leveling is to modulate the beta function at the interaction point. Our experience is that changes to magnet excitation are likely to result in increased loss rates. It is not clear how well we will be able to control the beam loss rates when changes are made to the machine parameters to keep the luminosity constant.

2. Tevatron Energy

We have specified that the Tevatron will run at 1000 GeV in Run II and future runs. We have finished an upgrade to the cryogenic cooling system and have accelerated protons to 980 GeV. A plan exists for getting to 1000 GeV. It involves running some satellite refrigerators at lower pressure (and therefore a lower temperature) and some shuffling of magnets. It is clear that the ultimate energy limit of the Tevatron lies near 1000 GeV, but it is not clear whether we will be able to run reliably at 1000 GeV. The answer will depend on how successful we are at optimizing the operation of the cyrogenic systems and how well we can mitigate the problem of low quench-current magnets.

3. Kickers

The injection kicker parameters (rise time, flattop length, and fall time) constrain the injection scenario. Currently, our proton kicker has a rise time of about 800 nsec, so we are effectively required to inject the protons in no more than 3 groups. In our machine experiments, we found that it was very difficult to achieve good coalescing efficiency with 12 bunches in the Main Ring. While we expect to make progress on the beam loading effects (including coherent instabilities) that are presumably responsible for this phenomena, we will probably build a new Tevatron short-batch injection kicker that will allow the injection of 1 to 4 proton bunches and sidestep the problems with coherent phenomena.

We also expect to build an agile, programmable, low-field kicker magnet (sometimes called a "bump" magnet) to enable the cancellation of the injection kicker ripple. This magnet could be operated from a program to cancel the imperfections in the injection kicker, in a feedback mode operating from the BPM system, or some combination of the two.

4. High beam currents

TeV33 requires here-to-fore unachieved beam currents in the Tevatron. Coupled bunch instabilities that have not been observed previously may become significant. Recent work on longitudinal instabilities has revealed a strong longitudinal, dipole mode=1, coupled-bunch instability. An observation of the instability is shown in Figure 2. This type of instability has also been observed in the Main Ring and the Booster. Continued work during the fixed target run should give us a better idea of what to expect in the TeV33 era.

5. Proton Removal

In order to recycle the antiprotons, they must be separated from the protons. We plan to eliminate the protons at the end of a Tevatron store, before deceleration. This plan has the advantage of making the deceleration process much easier because of the absence of beam-beam interaction effects. However, it does require removal of the protons from the Tevatron at high field, when the Tevatron magnets have the least margin against quenches induced by beam loss. While we have substantial experience with removing the protons with scrapers for special experiments (the proton and

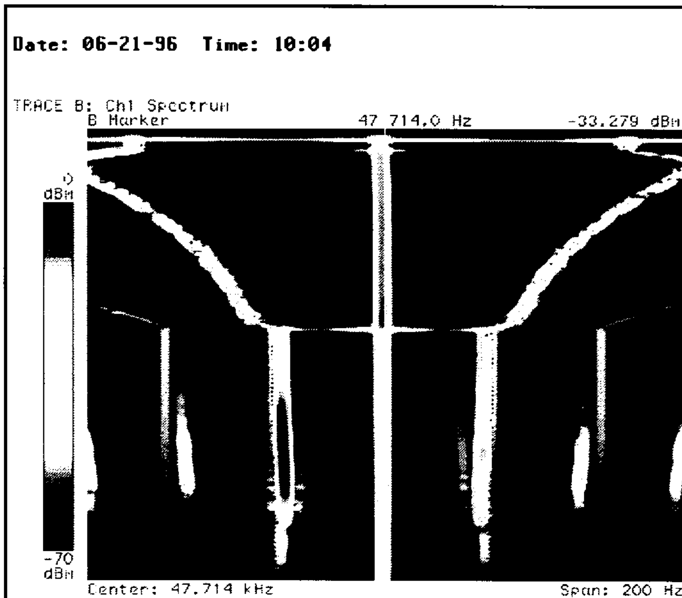

Figure 2. The longitudinal mode 1 instability in the Tevatron during flattop. This is a spectrograph from an HP-89440A analyzer where time increases vertically downwards, the frequency is shown horizontally, and the amplitude is indicated according to the color scale shown at the left. The central vertical line is the revolution frequency at 47.71 kHz, and the lines to either side are the upper and lower synchrotron sidebands. The modulation of the synchrotron frequency from about 80 Hz at injection to about 35 Hz is clearly seen. As the machine enters flattop, the synchrotron frequency becomes constant, and a dramatic growth in the amplitude of the lower sideband can be seen.

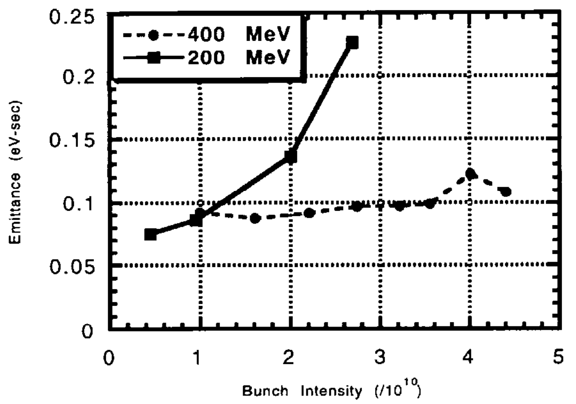

Figure 3. The Booster longitudinal emittance before and after the Linac upgrade.

antiproton beams are spatially separated), it typically takes half an hour to complete the process. Improvements both in technique and speed would be highly desirable.

V. PROTON BEAM ISSUES

The intensity and emittance of the proton beam are important both for the proton colliding beam and for antiproton production. The beam intensity issues can be discussed by considering each of the injectors in turn.

1. Antiproton Production

Run II specifications call for the Booster to produce 5×10^{12} protons per pulse with a maximum transverse emittance of 20π mm-mrad. The maximum Booster intensity achieved to date is 4.4×10^{12}, but the Booster normally operates at lower intensity in order to achieve the smaller emittance required by the Main Ring, where the effective acceptance is about 1.5π mm-mrad (unnormalized). The Booster is expected to reach its goal of 5×10^{12} after a period of operation with the Main Injector.

Improvements in Booster intensity beyond those already expected would be useful in producing lower emittance proton beams in collisions and for producing antiprotons at a higher rate. The Linac intensity is probably not of primary importance because beam can be injected for multiple turns using H^- ions. Most proposals for increased Booster performance involve fairly expensive Linac energy upgrades or construction of a larger aperture Booster to overcome space-charge effects. More modest plans to improve the Booster aperture may be effective. For the moment, it seems prudent not to rely on anything but incremental improvements in Booster intensity.

The Booster longitudinal emittance was specified to be 0.1-0.2 eV-sec for Main Injector operation, but the Booster appears to be capable of producing beams of 0.07 eV-sec [2]. Figure 3 shows the measured longitudinal emittance versus intensity in the Booster. The solid curve, represents measurements taken with the old, 200-MeV Linac; the dashed curve was taken after the upgrade to 400 MeV. The improvement in longitudinal emittance is not the direct result of the 400 MeV upgrade, but the result of suppressing a longitudinal coupled bunch instability.

The Main Injector was designed, in part, to accept the large emittance beams that one might expect on the basis of the extrapolation of the solid curve. We are left with the rather pleasant situation that the Booster beam is considerably smaller than the acceptance of the Main Injector. We may be able to take advantage of the unexpected improvement in beam emittance by stacking multiple pulses into the Main Injector.

The ultimate Main Injector intensity limitation is not known either experimentally or theoretically. However, compared to the Main Ring, the Main Injector has a much larger aperture and more attention has been paid to achieving a low beam impedance. These features are expected to result in substantially higher beam currents. One known limitation is the amount of rf power available: the Main Injector can support 10^{11} particles per bunch without modification (the nominal design intensity is 6×10^{10}).

The most promising strategy to increase the beam intensity seems to be to stack Booster pulses in the Main Injector. The most promising technique appears to be to coalesce bunches in the Main Injector with a technique known as "slip stacking". Slip stacking is particularly attractive because it requires no major hardware and could be implemented at the *beginning* of Run II. A cartoon of the stacking process is shown in Figure 4. The result of a simulation that models the single particle dynamics is shown in Figure 5. The results of the single particle dynamics are encouraging, but we need to refine the simulation and examine collective effects such as space charge, beam loading, and instabilities.

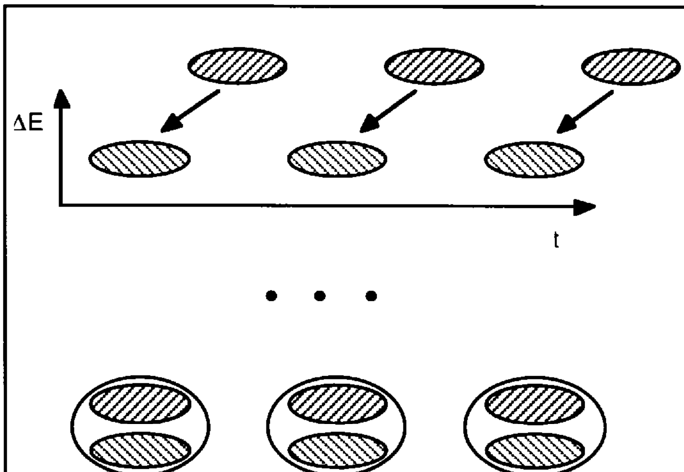

Figure 4. A cartoon of slip stacking. Two batches of beam are displaced in azimuth and energy (above), are brought close to each other, and are then combined in a single, large bucket.

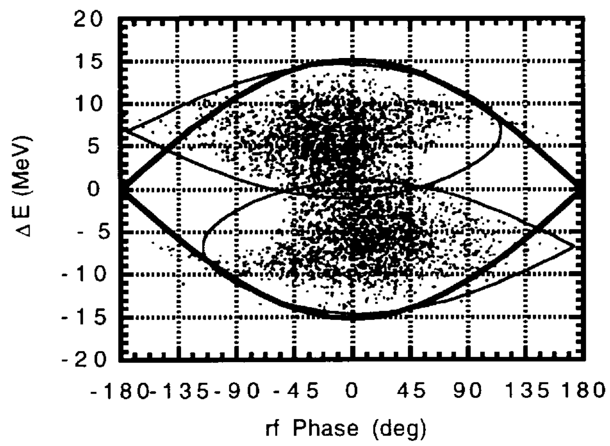

Figure 5. A simulation of slip stacking. The points represent the final phase space coordinates of the particles tracked in the presence of the two rf systems. The smaller curves are the moving rf buckets that would be generated by one system if the other system were not present. The large curve represents the stationary bucket into which most of the particles will be captured.

There are other ideas for increasing the number of protons targeted. Some of these are:

1. Increasing the Linac Energy
2. Replace the existing Booster with a "Super-Booster"
3. Betatron stacking in the Main Injector using the existing Booster.
4. Targeting the full Main Injector Ring.

These ideas have merit and may be pursued more vigorously in the future.

2. *Proton Colliding Beam*

The standard plan has called for coalescing of 12 batches simultaneously in Main Injector. Batches are coalesced by combining several bunches into a single, high-intensity bunch with a large, longitudinal emittance. The process is different in detail, but similar in effect to the slip-stacking described previously. Improvements in Main Injector intensity and longitudinal emittance mean that fewer bunches will be coalesced to achieve the required intensity and that the final longitudinal emittance will be lower.

We have had difficulty achieving the required bunch intensities when coalescing multiple batches because of coupled bunch instabilities. We also expect to continue to have these difficulties in the Main Injector era since the Main Ring rf cavities will be used in the Main Injector. We expect that we will eventually be able to solve these problems with a combination of feed-forward and feedback techniques. However, in case this problem should prove more difficult than expected, we also plan to build a faster injection kicker that would allow us to inject groups of 1-4 coalesced bunches.

VI. ANTIPROTON BEAM ISSUES

There are many technical issues involved with high luminosity colliders, but there is probably no more fundamental limitation than requirement that antiprotons must be produced at a higher rate than the rate at which they are consumed in collisions.

The Run II luminosity is expected to increase to 2×10^{32} $cm^{-2}sec^{-1}$ from the Run I value of 2×10^{31} $cm^{-2}sec^{-1}$. Much of the gain comes from a more efficient consumption of antiprotons. In particular, it is expected that the Main Injector will improve the antiproton transmission efficiency and that the Recycler will make possible the recovery ("recycling") of antiprotons at the conclusion of a Tevatron store.

1. *Role of the Recycler*

The capabilities of the Recycler ring appear to be worth a factor of 2-2.5 in luminosity relative to the Main Injector upgrade only. The Recycler Ring is an 8.9-GeV, permanent magnet, storage ring that will be built in the Main Injector tunnel.

A key ingredient in the Recycler plan is to provide a platform for eventual achievement of 1×10^{33} $cm^{-2}sec^{-1}$ in the Tevatron collider. To achieve this goal, the Recycler must not only serve as a repository for recycled antiprotons, but it must relieve the existing Accumulator Ring of responsibility for accumulation of large stacks.

2. *Antiproton production target issues*

The higher intensity proton beam expected at the antiproton target in Run II and TeV33 results in an increasingly hostile environment at the target station. Fermilab III already specifies a doubling of the beam targeted; TeV33 could result in a further doubling of the intensity. The antiproton source target area is a high radiation area that contains a number of high voltage devices.

One issue that is fairly well understood is the allowable peak energy deposition in solid targets. A sweeping system is envisioned to accommodate the higher intensity in Fermilab III. The same sweeping system is adequate for a doubling of the intensity in TeV33, but higher even intensities would require defocusing the beam (and a lower antiproton yield).

Information on the maximum allowable radiation dose of insulating materials is sketchy, but we typically exceed the high end of the ranges specified. Recently, a failure of the torlon® insulating material in the "pulsed magnet" was experienced.

We have seen a large number of lithium lens failures over the years. Few, if any, of these failures were the result of radiation damage. However, we could begin to see failures resulting from radiation damage. One proposed failure mode, production of gas through the reaction

$$^{6}Li + n \rightarrow {}^{3}H + {}^{4}He,$$

has been shown to be tolerable provided that lens is fabricated from pure ^{7}Li.

The radiation shielding issues are fairly well understood. Higher beam intensities will probably require modifications to the shielding or to the accessibility of the target hall and possibly improved air handling procedures (to reduce airborne contamination).

In summary, our current understanding is that targeting twice the Main Injector intensity (*i.e.*, 10^{13} per batch) is technically feasible.

3. Antiproton Acceptance

The antiproton beam circulating in the Debuncher has a measured size of 17π mm-mrad. It is believed that the cause of the small beam size is a gross misalignment (quadrupole steering) in the AP-2 injection line.

The original design of the Debuncher was for a 20π mm-mrad acceptance, but it was upgraded to a (design) 30π mm-mrad. Operationally, the Debuncher is typically measured to have an aperture of 26π mm-mrad. Optimistically, one might expect to achieve an aperture of 32π mm-mrad by rebuilding the injection devices and by improving orbit control.

The currently installed gamma-t jump can be pulsed to increase the Debuncher momentum spread from 4.0% to 4.9%. An increase in Li lens gradient from 750 T/m to 900 T/m would result in a gain in yield of 11%. Increasing the gradient further to 1300 T/m results in an additional 17% gain in yield.

A summary of the antiproton source acceptance upgrades is given in Table III. One of the goals of the TeV33 group is to develop a more detailed plan to increase the Debuncher acceptance and to refine the estimates of the antiproton flux that may be obtained.

Table III. Summary of Antiproton Acceptance Upgrades

Upgrade	(Ideal) Gain
$\varepsilon=17\pi\rightarrow26\pi$ mm-mrad	56%
Lens 750→900 T/m	11%
$\Delta p/p=4.0\rightarrow4.9\%$	23%
$\varepsilon=26\pi\rightarrow32\pi$ mm-mrad	30%
Lens 900→1300 T/m	17%
Combined Total	223%

4. Beam Cooling Issues

For Run II, we plan to upgrade the existing 2-4 GHz cooling system in the Debuncher and to upgrade the 1-2 GHz stack tail cooling system to a 2-4 GHz cooling system. We plan to use stochastic cooling in the Recycler initially. These upgrades will result in stacking rates of 2×10^{11}/hour for Run II.

A preliminary look at stochastic cooling in the Debuncher and the Accumulator suggests that 4-8 GHz cooling systems can accommodate the factor of 4-5 increase in flux. The Debuncher systems would achieve a factor of 4 increase in cooling rate by doubling the bandwidth (a factor of 2) and by reducing the mixing factor (the second factor of 2). The stack tail system in the Accumulator would benefit from an increased bandwidth (a factor of 2), but would have half its cooling load assumed by the Recycler Ring. An important ingredient of this effort is an R&D effort to produce high sensitivity 4-8 GHz pickups and kickers.

The Recycler electron cooling system is expected to be fully operational and will be used as an additional system to longitudinally stack the antiprotons. Early concepts of electron cooling were based on the Pelletron. This device requires high dc voltages, excellent beam recovery efficiency, and a substantial amount of civil construction. More recent ideas include the development of an induction Linac including a recirculation path or a Betatron.

VII. CONCLUSION

The plan for TeV33 is still being developed. Some of the issues we hope to examine at Snowmass include collective effects in slip stacking, possible store parameters, electron beam cooling technologies, and the effect of the beam-beam interaction.

VIII. ACKNOWLEDGMENTS

This work was performed at Fermi National Accelerator Laboratory, which is operated by Universities Research Association, Inc., under contract DE-AC02-76CH03000 with the U. S. Department of Energy.

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